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Neutral kaons as decay products and analyzers of heavier flavors [1]

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Abstract

Cascade decays of heavy flavor hadrons to states with neutral kaons are discussed as an instrument for detailed studies of the heavy hadron properties. For neutral flavored mesons the well-known kaon oscillations provide a unique experimental possibility of relating lighter/heavier eigenstate masses to (approximate) even/odd eigenstate CP-parities and to longer/shorter eigenstate lifetimes. As a result, they allow to eliminate sign ambiguities of CP-violating parameters and, therefore, to check the Standard Model (or to find New Physics). Specifically for charmed hadrons, both neutral/charged mesons and baryons, the secondary kaon oscillations permit unambiguous separation of Cabibbo-allowed and doubly-suppressed decay amplitudes, including measurement of their relative phases. For neutral D-meson decays the kaon oscillations can also discriminate, again unambiguously, between effects of D-meson mixing and interference of suppressed/allowed amplitudes. Another problem discussed is the influence of kaon CP-violation on the amplitude structure and on phenomenology of CP-violation in heavy hadron decays.

1 Introduction

CP-violation in heavy flavors is becoming an object of experimental studies [1-3]. However, many related theoretical problems are not quite understood yet. For example, it was noted only recently (see, e.g. [4-8]) that some discrete ambiguities may appear when extracting CP-violating parameters from experiment and comparing them with theory. Such ambiguities may shadow manifestations of New Physics (see discussion in [5, 9]). Specific problems arise also in decays of D-mesons, where doubly Cabibbo-suppressed transitions may imitate flavor mixing effects.

Discussed in this talk is the unique role of neutral kaons produced in decays of heavier flavors. Well-studied strangeness oscillations are sensitive to the relative initial content of K^0 and $\overline{K}^0$. Therefore, they may be used to analyze detailed properties of the decays and heavier flavor hadrons themselves, just as, say, asymmetric decays of hyperons are used to analyze the hyperon polarization and properties of hyperon production. At this way one becomes able to eliminate any ambiguities of CP-violating parameters. Decays to neutral kaons are capable as well to separate "right" and "wrong" strangeness transitions (Cabibbo-allowed and Cabibbo-suppressed amplitudes) for charmed and beauty hadrons, both neutral and charged mesons or baryons, again unambiguously. Also discussed are unfamiliar manifestations of kaon CP-violation in heavy meson decays.

2 Amplitude ambiguities and their nature

Let us consider, in the standard manner, decays of neutral flavored spinless mesons M and $\overline{M}$. The most popular way to search for CP-violation is to study decays

$$M(\overline{M}) \to X_{CP} \tag{1}$$

into a state of definite CP-parity. CP-violation in the decays may be described by the parameter

$$\lambda_X = \frac{q_M}{p_M}\,\frac{A_{\overline{M}X}}{A_{MX}}\,. \tag{2}$$

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It is rephasing invariant and is commonly considered as unambiguous. However, there is an intrinsic sign ambiguity hidden in this parameter. Ambiguities described in the literature look differently in different papers (e.g., [4, 7, 8]), but all of them are really related to just this sign ambiguity.

We can reveal the ambiguity by expressing λ_X through decay amplitudes $A_X^{(1)}$ and $A_X^{(2)}$ of the eigenstates $M^{(1)} = p_M M + q_M \overline{M}$, $M^{(2)} = p_M M - q_M \overline{M}$. In such a way we obtain

$$\lambda_X = \frac{A_X^{(1)} - A_X^{(2)}}{A_X^{(1)} + A_X^{(2)}}\,, \quad \mathrm{Re}\lambda_X = \frac{|A_X^{(1)}|^2 - |A_X^{(2)}|^2}{|A_X^{(1)} + A_X^{(2)}|^2}\,, \quad \mathrm{Im}\lambda_X = \frac{2\,\mathrm{Im}(A_X^{(1)}\, A_X^{(2)*})}{|A_X^{(1)} + A_X^{(2)}|^2}\,. \tag{3}$$

This expression clearly shows that λ_X changes its sign under interchange of $M^{(1)}$ and $M^{(2)}$. Thus, to fix the sign of λ_X we need to identify who is who in the set of the eigenstates. In other words, definition (2) should be appended by some physical labeling for the eigenstates.

Consider the situation in more detail. Decays (1) go along two branches: $M(\overline{M}) \to M^{(1)} \to X_{CP}$ and $M(\overline{M}) \to M^{(2)} \to X_{CP}$. They produce separate contributions to the decay amplitude which can interfere. Time distribution of any decay (1) contains two kinds of terms linear in λ_X, both unambiguously measurable. Direct contributions of the two branches combine into the term proportional to

$$\mathrm{Re}\lambda_X \cdot \sinh\frac{(\Gamma^{(1)} - \Gamma^{(2)})t}{2}\,,$$

while interference of the branches gives the term proportional to

$$\mathrm{Im}\lambda_X \cdot \sin(m^{(1)} - m^{(2)})t\,.$$

Structure of these terms allows to formulate the ambiguity problem more explicitly.

There are three possible ways of labeling the eigenstates:

- Lifetime labeling identifies the states as longer or shorter lived. Then the sign of $\Delta\Gamma$ is fixed by definition, so $\mathrm{Re}\lambda_X$ is experimentally unambiguous. But the sign of Δm is generally unknown, and the sign of $\mathrm{Im}\lambda_X$ appears to be ambiguous.

- CP-parity labeling identifies the states (though may be approximately) as CP-even or CP-odd. Here we define (see, e.g., ref.[4]) that $M^{(1)}$ has the same (approximate) CP-parity as the final state X_{CP} if it decays to X_{CP} more intensely than $M^{(2)}$. This means that $|A^{(1)}| > |A^{(2)}|$, and so this definition fixes the sign of $\mathrm{Re}\lambda_X$ through eq.(3). The sign of $\Delta\Gamma$ becomes measurable, but the signs of Δm and $\mathrm{Im}\lambda_X$ stay unknown.

- Mass labeling identifies the states as heavier or lighter. Here the sign of Δm is fixed, and $\mathrm{Im}\lambda_X$ may be measured unambiguously. But such convention does not fix the sign of $\Delta\Gamma$, and thus $\mathrm{Re}\lambda_X$ has the sign ambiguity (see, e.g., ref.[8]).

It is evident now that all experimental sign ambiguities would be eliminated if we could relate those three labelings to each other.

The lifetime and CP-parity labelings can be related to each other in a straightforward way by comparing time-dependences of decays into final states of different CP-parities. However, their relation to the mass labeling is not so simple.

We can illustrate the general situation by comparing it to the well-studied case of neutral kaons. Kaon eigenstates are defined at present as K_S amd K_L through their lifetimes. Correspondence of the lifetimes and CP-parities has been achieved in decays to 2π and/or 3π. Note that similar attempt was recently made also for D-mesons [10], but the achieved precision appeared still insufficient to notice any difference of the two lifetimes.

Kaon mass labeling, i.e. identification of K_L as the heavier state, became possible only after special complicated experiments on coherent regeneration (their summary see in [11]) which related to each other the masses and CP-parities of kaon eigenstates. Without such mass labeling the standard CP-violating kaon parameters η could be measured only up to the sign of $\mathrm{Im}\eta$.

For B- and D-mesons the coherent regeneration cannot be observed because of their too short lifetimes. Instead one may use some theoretical assumptions (e.g., [7]). However, there should exist direct

experimental ways to relate all three kinds of labeling, independently of any theoretical assumptions. One of them is described in the next section. Interestingly enough and similar to how it was for kaons, the direct experimental interrelation of eigenmasses and eigenwidths appears to be impossible for B- and D-mesons as well (the corresponding discussion see in [13]). Both masses and widths can be directly related only to CP-parities of the eigenstates, and only after that to each other.

3 Neutral kaons as analyzers of heavier flavors

It is well known that weak decays of hyperons, being asymmetric due to parity violation, are good analyzers which may be used to measure hyperon polarization in various processes. In direct analogy, it was suggested [12] that the neutral kaons, with their decay oscillations, may be used to analyze properties of heavy flavor hadrons. Here we only briefly explain the main ideas underlying such an approach. More technical details, with accurate formulas, may be found in [12, 13].

Instead of decays (1) we consider now decays

$$M(\overline{M}) \to X_{CP} K^0(\overline{K}^0) \tag{4}$$

and assume that X_{CP} has definite values of both CP-parity and spin. Generally, there are two possible kinds of flavor transitions, $M \to K^0$ and $M \to \overline{K}^0$ (and two charge conjugate ones), with corresponding different amplitudes. The very essential point is that a definite coherent mixture of M and $\overline{M}$ just before the decay (4) produces some different, but also definite coherent mixture of K^0 and $\overline{K}^0$ just after the decay. As a result, time evolution of neutral kaons after decay (4) coherently continues evolution of the flavored neutral mesons before the decay [14].

The neutral kaons may be observed only through their decay, so we really have cascade decays with two stages and two decay times, t_M and t_K (we mean not average lifetimes, but event-by-event times). Flavor oscillations at the two stages are correlated[2]. Such coherent double-flavor oscillations produce generally non-factorisable dependence on the two decay times. It is rather complicated (see [12, 13]), and for better understanding its main features we may first simplify it by assuming exact CP-conservation (for both M-mesons and kaons!). Then the states $X_{CP}K_S$ and $X_{CP}K_L$ have definite CP-parities. Eigenstates $M^{(1)}$ and $M^{(2)}$ also have definite CP-parities, which may be used as their labels (just as K_1 and K_2 for neural kaons before discovery of CP-violation). Of course, only two transitions, say,

$$M^{(1)} \to X_{CP}K_L\,, \quad M^{(2)} \to X_{CP}K_S \tag{5}$$

are possible here, instead of four ones in the general case (initial and final CP-parities should be the same).

If we observe the secondary kaons by their decays to 2π or 3π modes, then only one of transitions (5) contributes (recall the assumption of exact CP-conservation!). As a result, dependences on t_M and t_K become factorised. Such decay chains allow to relate lifetimes and CP-parities of $M^{(1,2)}$. But if we use semileptonic kaon decays, with contributions from both K_L and K_S, then both transitions work; time distribution contains their interference term proportional to

$$\cos(\Delta m_M t_M - \Delta m_K t_K)\,.$$

Its measurement, evidently, determines the sign of Δm_M in respect to the known sign of Δm_K and, therefore, relates masses and CP-parities of M-eigenstates.

CP-violation complicates this picture due to interferences of all four cascade branches [12, 13]. Nevertheless, studies of decays (4) are still capable to relate mass labeling of heavy meson eigenstates with their CP-parity labeling and, then, with lifetime one. Therefore, as explained above, such studies can eliminate all experimental ambiguities in CP-violating parameters.

Decays of charmed particles suggest one more test-ground for the analyzing power of neutral kaon oscillations. As a rule, B-meson decays to neutral kaons have only one flavor transition (and its charge

[2] The term "cascade mixing" [15] looks not adequate, since mixings at the two stages have the usual standard form and are not related to each other; related are only flavor oscillations.

conjugate), $B \to K$ or $B \to \overline{K}$ (compare decays considered in refs. [12] and [16]). On the opposite, D-mesons, neutral and charged (and even charmed baryons), always have both kinds of transitions. One of then is doubly Cabibbo-suppressed, i.e. relatively small (about 3% in the amplitude). Nevertheless, it is of special interest: it exemplifies a new kind of weak transitions and might demonstrate different (larger?) CP-violation. The same is true, of course, for decays to charged kaons as well, which may produce kaon of "wrong" sign. However, decays to neutral K's have an essential difference. Final states for the charged kaon case are not coherent, and one can compare only absolute values of the decay amplitudes. As was first noticed in [17] (see also ref.[18]), decays to neutral kaons produce coherent states and allow to measure as well the relative phase of the amplitudes.

The current literature contains suggestions to realize this by measuring probabilities of transitions $D \to K_S$, $D \to K_L$ [19, 20]. But in such an approach the relative phase of the transition amplitudes cannot be measured, and separation of the amplitudes for $D \to \overline{K}^0$, $D \to K^0$ appears to be ambiguous. Measurement of strangeness oscillations for the secondary neutral kaons makes the amplitude separation for different flavor transitions quite unambiguous (more details see in [13]; similar ideas were discussed in [18, 21]). We emphasize that the oscillations may provide as well clear separation of two sources of "wrong" strangeness production, the Cabibbo-suppressed transition and mixing of initial neutral D-mesons.

4 Secondary kaon CP-violation

Manifestations of kaon CP-violation in kaon decays has been studied in all detail, at least phenomenologically. However, production of neutral kaons (in particular, in decays of heavier particles) provides different manifestations, not quite familiar. Some of them look rather formal at present, b ut may become physically meaningful in future experiments. Moreover, they might be useful for studying CP-violation related to heavier hadrons. Here we consider two kinds of such manifestations: for amplitudes, and for decay yields.

We begin with the problem, what are amplitudes for production of $K_{S,L}$, say, in decays (4) of the meson M. Since $K_{S,L} = p_K K^0 \pm q_K \overline{K}^0$, it seems natural to express those amplitudes through the amplitudes $A^{(X)}_{MK}$ and $A^{(X)}_{M\overline{K}}$ of flavor transitions $M \to K^0$ and $M \to \overline{K}^0$ as

$$p^*_K A^{(X)}_{MK} \pm q^*_K A^{(X)}_{M\overline{K}} \,. \tag{6}$$

Such expressions indeed exist in the literature, but they are incorrect. To understand why and to find correct expressions we first recall the general meaning of amplitudes.

When given an initial state $|i>$ and the S-matrix, the amplitudes A_{ik} of transitions $|i> \to |k>$ are defined by decomposition of the final state $S|i>$ in terms of some set of states $|k>$:

$$S|i> = \sum_k A_{ik}|k> \ .$$

If the set is orthonormalized we arrive at the canonical expression $A_{ik} = < k|S|i >$. However, this expression is inapplicable if the states $|k>$ are not orthogonal.

Let us apply this consideration to decays (4). Decay of the meson M produces the kaon state (up to normalization)

$$A^{(X)}_{MK} K^0 + A^{(X)}_{M\overline{K}} \overline{K}^0 \,.$$

To find amplitudes of transitions $M \to K_{S,L}$ we should decompose this final state in terms of $K_{S,L}$ and extract the corresponding coefficients. Since

$$K^0 = (K_S + K_L)/(2p_K) \,, \quad \overline{K}^0 = (K_S - K_L)/(2q_K) \,,$$

we finally obtain

$$A^{(X)}_{MS} = \frac{A^{(X)}_{MK}}{2p_K} + \frac{A^{(X)}_{M\overline{K}}}{2q_K} \,, \qquad A^{(X)}_{ML} = \frac{A^{(X)}_{MK}}{2p_K} - \frac{A^{(X)}_{M\overline{K}}}{2q_K} \,. \tag{7}$$

Amplitudes for decays of $\overline{M}$ may be found in the same way.

Expressions (6) and (7) coincide if $|p|^2 = |q|^2 = 1/2$, i.e. when CP is conserved and the states $K_{S,L}$ are orthogonal. They differ when CP is violated and the states $K_{S,L}$ are not orthogonal. Using decomposition over non-orthogonal set of states is non-standard, but looks natural for kaons with CP-violation. Expressions (7) just correspond to those used earlier in refs. [17, 12, 13]. Of course, expressions (6) and (7) for amplitudes lead to different expressions for decay probabilities as well.

There is one more consequence of kaon CP-violation for processes with neutral kaons produced. Let us compare decays of initially pure states K^0 and/or $\overline{K}^0$ into a particular mode. Their time dependences generally oscillate. The oscillations would be absent for some decay modes if CP were conserved; they are present for any mode when CP is violated. These oscillations are different for initial K^0 or $\overline{K}^0$. As a result, decay yields at a particular time moment (and even total decay yields) are also different for initially pure K^0 or $\overline{K}^0$. Of course, the relative difference is of the order $|\eta|$. Similar difference, generally, exists for any coherent mixture of K^0 and $\overline{K}^0$ having no symmetry under their interchange.

Now, compare decays of, say, D (neutral or charged) and $\overline{D}$, with neutral kaons produced. Assume that the D-decay generates a kaon system $aK^0 + b\overline{K}^0$. The conjugate $\overline{D}$-decay without any CP-violation, direct or in D-mixing, generates the conjugate system $a\overline{K}^0 + bK^0$. Using any particular way to detect the secondary neutral kaons (e.g., particular decay modes and/or particular interval(s) of kaon decay times) will lead to different results for D and $\overline{D}$ due to kaon CP-violation. The difference is still present after integration over t_K. Theoretically, such t_K-integrated effect was first demonstrated some years ago [17] for the sequence $D^\pm \to \pi^\pm K^0(\overline{K}^0),\ K^0(\overline{K}^0) \to \pi^+\pi^-$. Recent (but not quite correct) discussion of the small-t_K region see in [22]. We emphasize that similar effects of the kaon CP-violation should appear in all decays of heavier flavor hadrons, both mesons and baryons, to neutral kaons.

Presence of D-meson CP-violation does not eliminate the discussed effect. Moreover, kaon CP-violation in cascade decays appears to be coherent with the D-meson CP-violation and may be used to analyze its details. Thus, we may have one more example of the analyzing power of neutral kaons.

5 Conclusion

In summary, we see that neutral kaons being decay products may provide the great analyzing power for very detailed studies of heavier flavor hadrons and their decays.

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